MC Simulation of Silicon Pixel Detector

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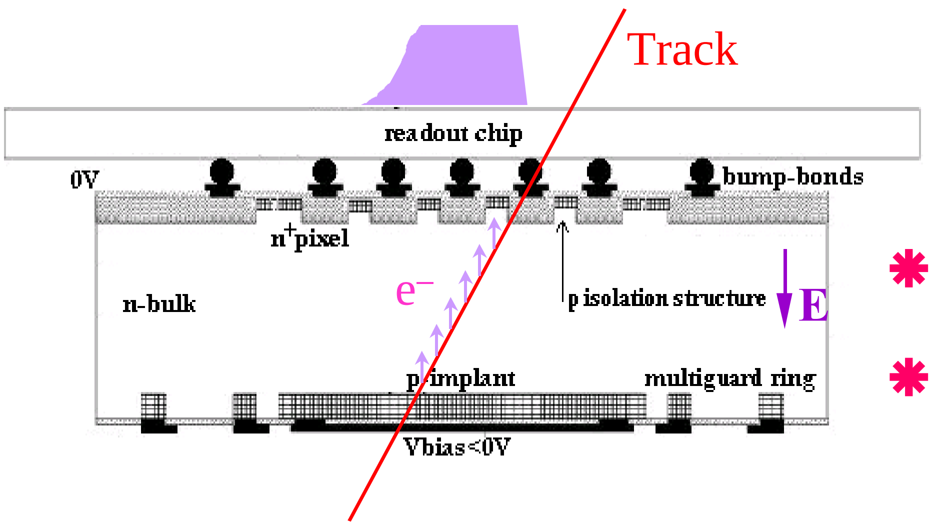
Readout Signal Simulation



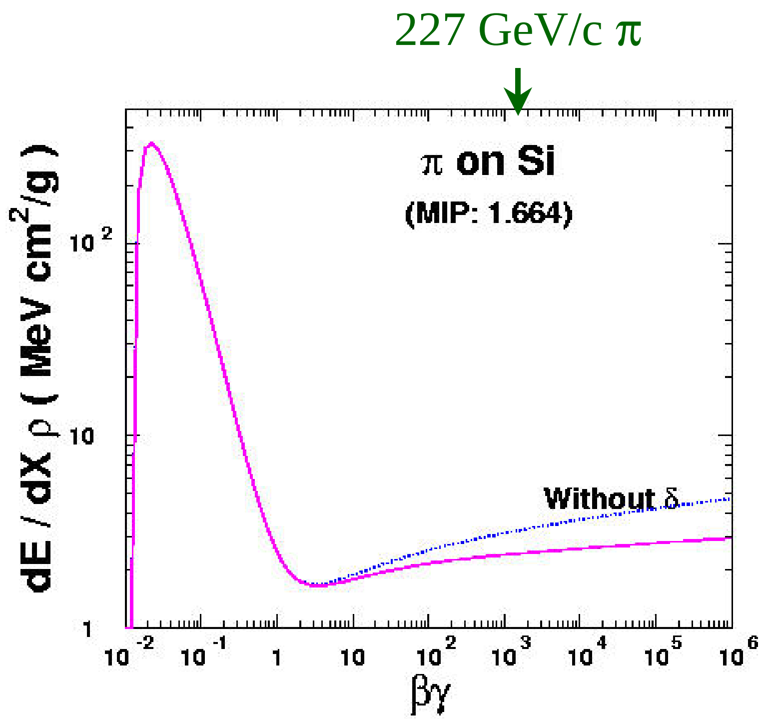
- Energy deposition by charged track along its path length, and production of electron/hole pairs
- Electron clouds drifting towards readout pixel in electric field (corresponding to doping and bias voltage applied)
- Electron cloud spread due to diffusion
- Magnetic field deflection (our sensors will be in dipole field of 1.6 T)
- Realistic front end electronics (noise, threshold, digitization accuracy)

Energy Deposition

$$\frac{dE}{\rho dx} = 2\pi N_{Av} r_e^2 m_e c^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\ln\frac{2m_e c^2\beta^2\gamma^2 T_{max}}{I^2} - 2\beta^2 - \delta\right]$$

$$\xi = 2\pi N_{Av} r_e^2 m_e c^2 \frac{Z}{A}\frac{1}{\beta^2}\cdot\rho\cdot\delta x$$

- Density effect: δ
- At high $\beta\gamma$, radiative losses need to be considered (+7%)
- Thin material (280µm silicon): $\xi = 5.0$ keV, $\xi / I_0 = 29$



Production of δ-ray

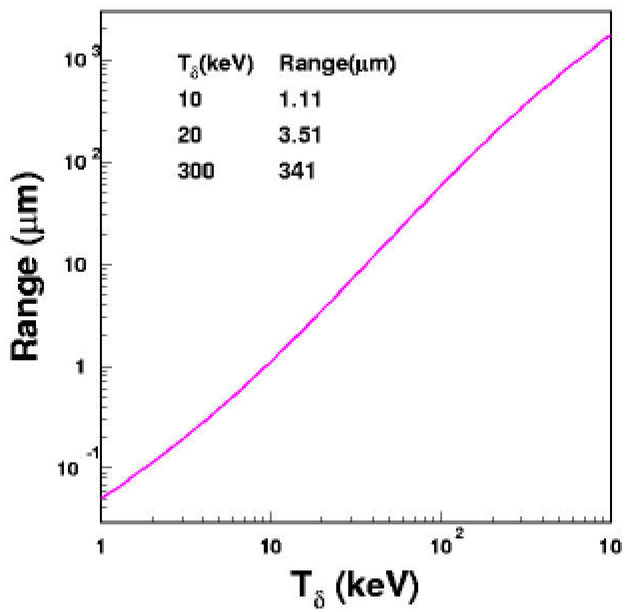
$$\frac{dN}{dT\cdot dx}=\left(\rho\cdot 2\pi N_{Av}r_e^2 m_e c^2\frac{Z}{A}\right)\times\frac{1}{\beta^2}\cdot\frac{1}{T^2}\left(1-\beta^2\frac{T}{T_{max}}\right)$$

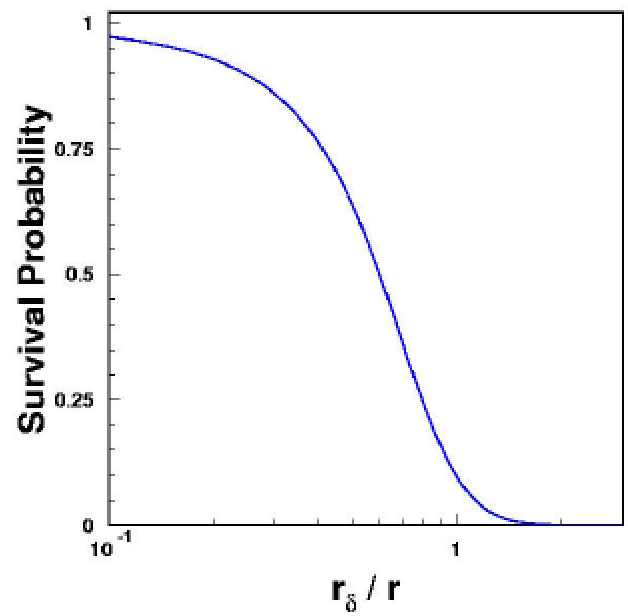
$$\cos^2\theta=\frac{T}{T+2m_e}\bullet\frac{T_{max}+2m_e}{T_{max}}$$

- Number of δ-ray: $\langle N\rangle \approx 0.5$ (T_{cut}=10 keV, d=280 μm)
- Kinetic energy according to dN/dT
- Polar angle θ is calculated
- Azimuthal angle ϕ generated isotropically

Ionization of δ-ray

- The δ-ray range is calculated
- The length of δ-ray ← Survival probability function
- Ionization uniformly
- δ-ray escape (only 1/4 of energy collected)





Excitation and Ionization

- Urbán model (thin material: $\xi/I = 29$ for 280μm silicon)
- Excitations: E_1 E_2 Ionization: E_3

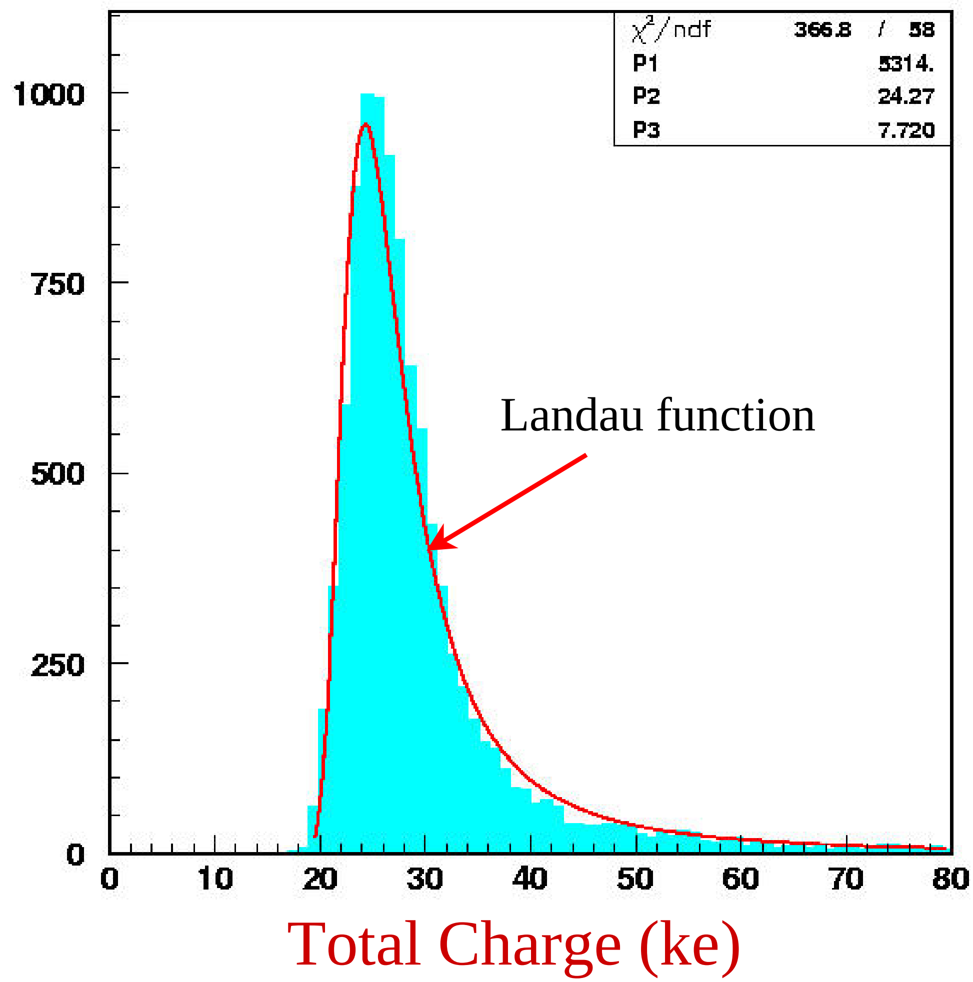
$$E_2 = 10 \cdot Z^2 \text{eV}$$
$$E_1 = \left(I / E_2^{f_2}\right)^{1/f_1}, \quad f_2 = 2/Z, \; f_1 = 1 - f_2$$
$$g(E_3) \propto 1/E_3^2, \quad I < E_3 < E_{max}$$

- Cross-sections

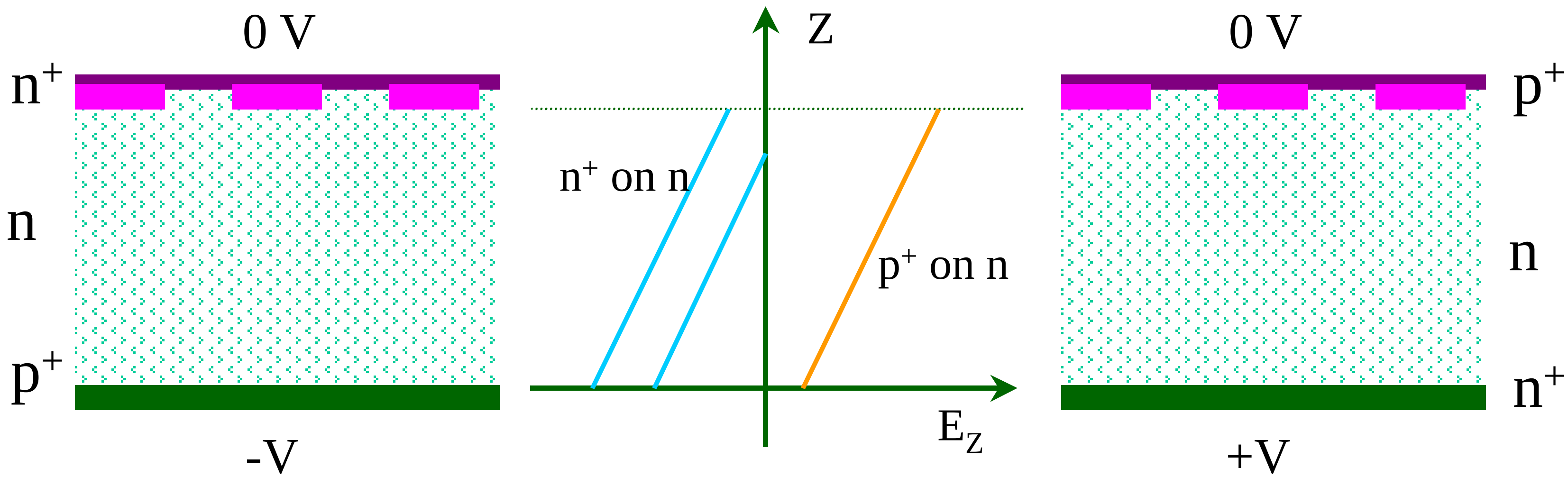
$$\Sigma_i = C \cdot (1-r) \cdot \frac{f_i}{E_i} \cdot \frac{\ln(2m\beta^2\gamma^2 / E_i) - \beta^2}{\ln(2m\beta^2\gamma^2 / I) - \beta^2}$$
$$\Sigma_3 = C \cdot r \cdot \frac{E_{max}}{I(I + E_{max}) \cdot \ln(E_{max} / I + 1)}$$

- dE/dx: $C \cdot (1-r)$ for excitation and $C \cdot r$ for ionization

Total Charge



Electric Field



$$\left|E_Z\right| = \frac{V}{d} \mp \frac{(2Z - d)V_D}{d^2}$$

Mobility

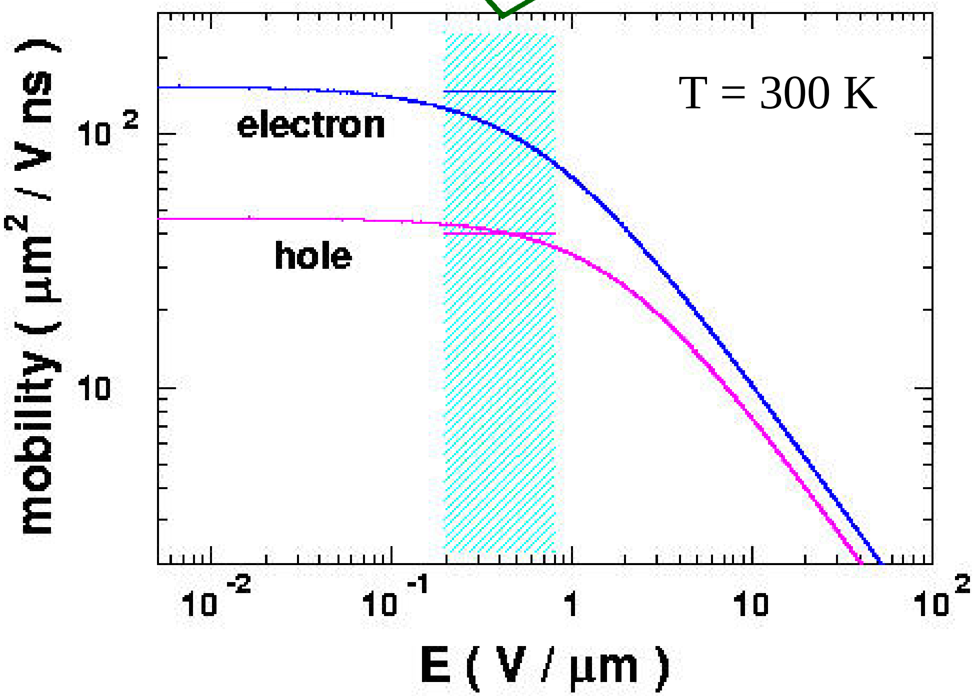
$$\mu = \mu_0 \Big/ \left(1 + \left(\frac{E}{E_C}\right)^{\beta}\right)^{1/\beta}$$

$$\mu_0^n = 153.3 \cdot \left(\frac{T}{300}\right)^{-2.42} \quad \mu m^2 / V \cdot ns$$

$$E_C^n = 0.698 \cdot \left(\frac{T}{300}\right)^{1.55} \quad V / \mu m$$

$$\beta^n = 1.109 \cdot \left(\frac{T}{300}\right)^{0.66}$$

$V_{applied} = 140$ V
$V_{depletion} = 85$ V
$d = 280\ \mu m$



Magnetic Field

$$\vec{E} = E \cdot \vec{e}_Z, \quad \vec{B} = B_X \cdot \vec{e}_X + B_Y \cdot \vec{e}_Y + B_Z \cdot \vec{e}_Z$$

$$V_Z = \frac{1+\mu_H^2 B_Z^2}{1+\mu_H^2 B^2} \cdot \mu E = \mu_{eff} E \qquad \mu_H = \begin{cases} 1.15 \cdot \mu & \text{electron} \\ 0.72 \cdot \mu & \text{hole} \end{cases}$$

$$\tan \vartheta_X = \frac{B_X B_Z \mu_H^2 \pm \mu_H B_Y}{1+\mu_H^2 B_Z^2} \qquad \tan \vartheta_Y = \frac{B_Y B_Z \mu_H^2 \mp \mu_H B_X}{1+\mu_H^2 B_Z^2}$$

Charge Cloud Spread

- Radius of ionization trail:

$$R = \hbar c\ \beta\gamma / I \quad (\sim 2\mu m)$$

- Diffusion:

$$D = kT\mu / q, \quad \sigma_X = \sigma_Y = sqrt(2Dt)$$

Electronics

- Noise (preamplifier, ADC)
- Non-uniform threshold
- Gain uncertainty
- ADC precision

Cluster Algorithm

- Similar as test beam offline analysis
- Plan: study overlapped cluster
- This might also improve the resolution by reducing the effect of δ-ray

Charge Sharing

Fraction of Cluster (row) size

Measurement

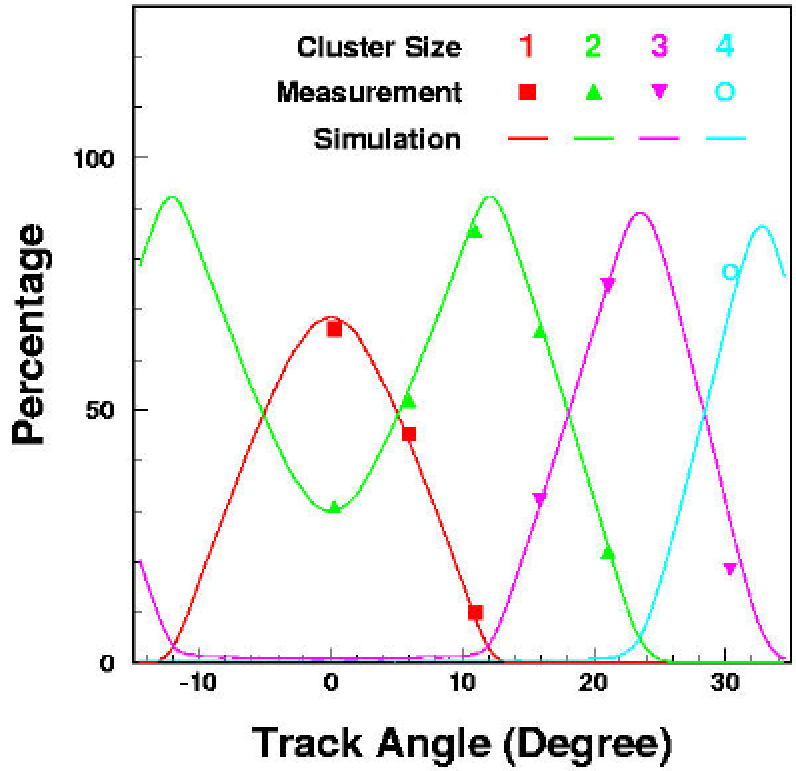
Angle \ Size	1	2	3	4	≥5
0°	.665	.311	.012	.006	.006
5°	.452	.518	.016	.006	.008
10°	.099	.857	.028	.007	.009
15°	.001	.658	.320	.010	.011
20°	.000	.221	.746	.019	.014
30°	.000	.000	.185	.775	.040

Simulation

Angle \ Size	1	2	3	4	≥5
0°	.684	.300	.009	.004	.003
5°	.436	.547	.010	.004	.003
10°	.087	.886	.017	.005	.005
15°	.000	.676	.312	.006	.006
20°	.000	.229	.754	.010	.007
30°	.000	.000	.279	.704	.017

FPIX0 CiS p-stop $Q_{th} = 2500\ e^-$

$V_{bias} = -140V$ $V_{depl} = -85V$

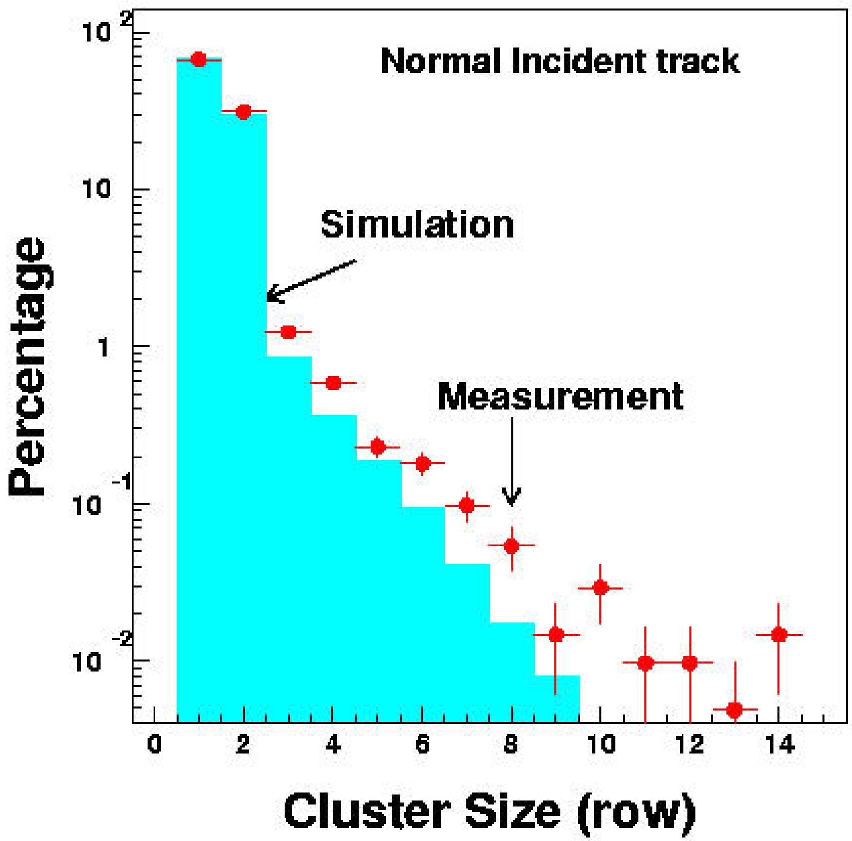


Large Size Cluster

Simulation has less large size cluster than measurement

Source ?

FPIX0-pstop



Charge Sharing

Fraction of Cluster (row) size

Measurement

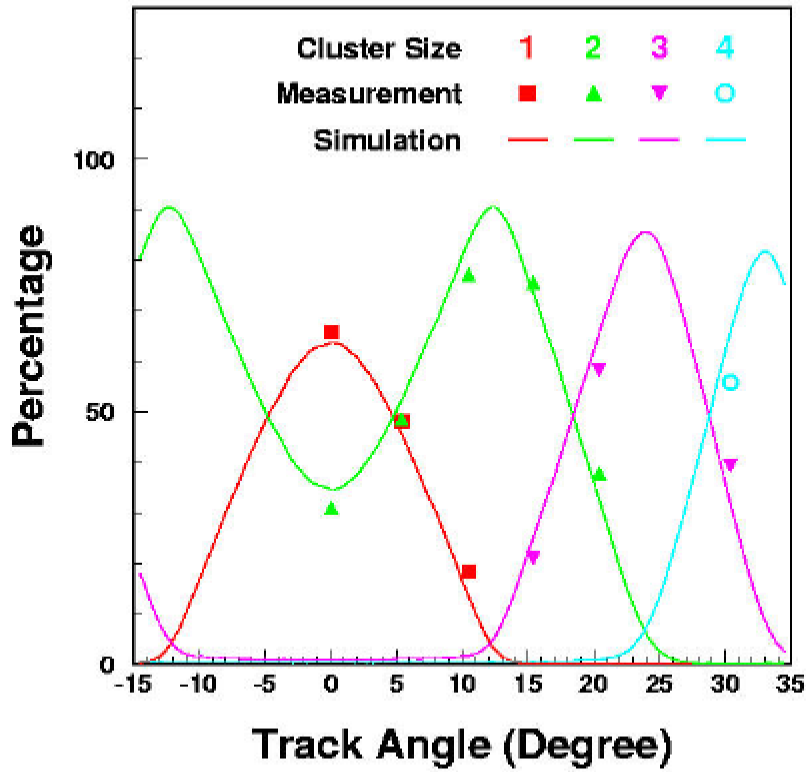
Angle \ Size	1	2	3	4	≥5
0°	.660	.311	.016	.006	.007
5°	.482	.486	.018	.007	.007
10°	.183	.771	.028	.008	.009
15°	.012	.756	.211	.010	.011
20°	.006	.379	.582	.018	.015
30°	.006	.011	.393	.558	.032

Simulation

Angle \ Size	1	2	3	4	≥5
0°	.636	.346	.009	.004	.005
5°	.456	.525	.011	.004	.004
10°	.135	.838	.017	.005	.005
15°	.002	.736	.250	.006	.006
20°	.000	.328	.654	.010	.008
30°	.001	.002	.320	.657	.020

FPIX1 Seiko p-stop $Q_{th} = 3780\ e^-$

$V_{bias} = -75V$ $V_{depl} = -45V$

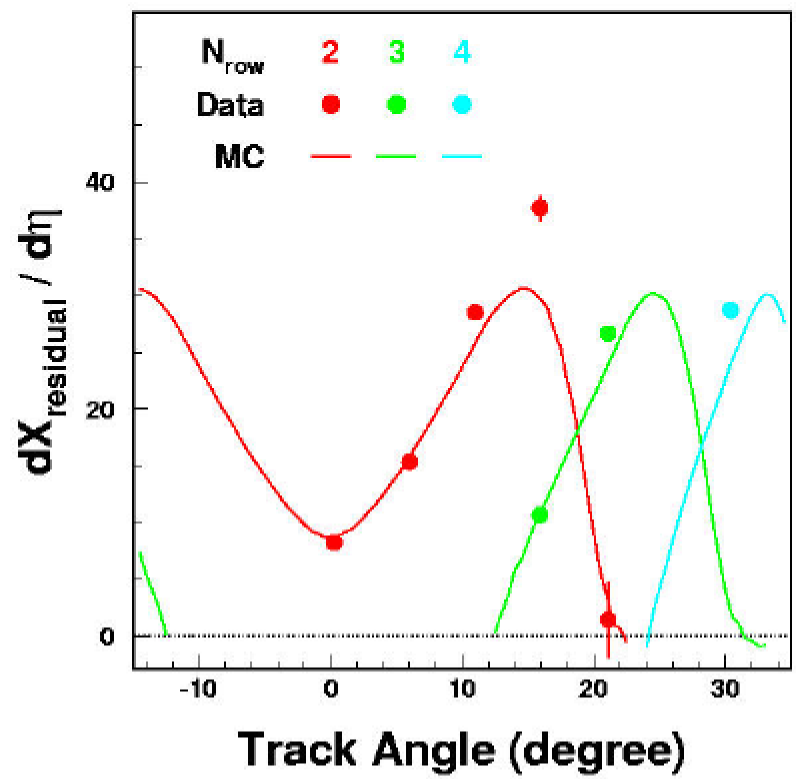


Reconstruction

Linear η correction applied

$$X_{residual} = X_{track} - X_{recon}$$

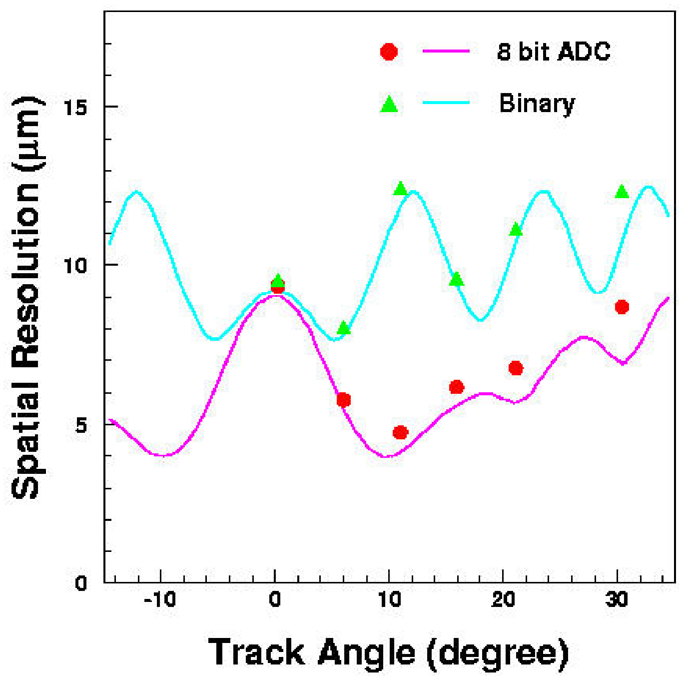
$$\eta = \frac{Q_{right} - Q_{left}}{Q_{right} + Q_{left}}$$



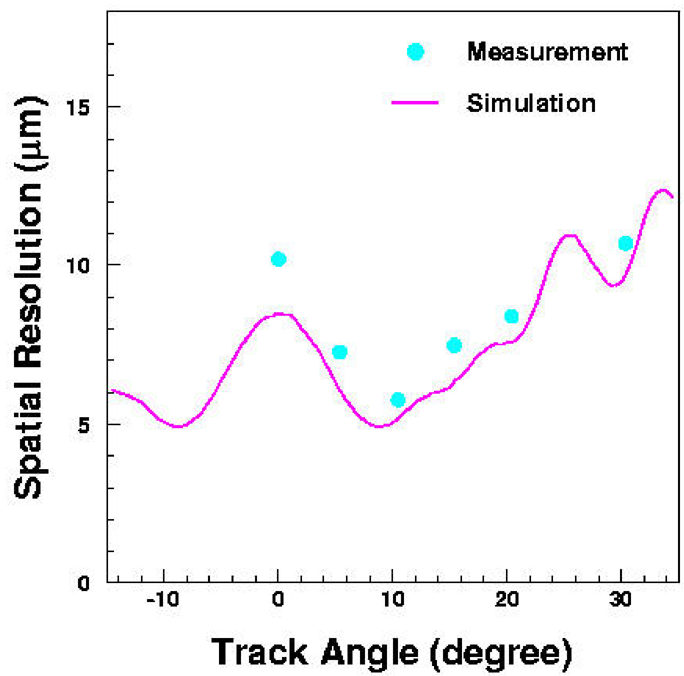
Resolution vs angle

- No track projection error subtracted from the measurement
- Resolution distribution agrees with simulation
- Binary resolution degraded from 8-bit ADC

FPIX0 p-stop



FPIX1 p-stop



Summary

- New version simulation program works quite well
- There are not much can be tuned
- Plug the code into BTeV simulation
- Two approaches need to be evaluated
  - Use GEANT simulation in energy deposition
  - Use the energy deposition simulation of this program

Beam Test Track Angle

Angle (°)	FPIX0 p-stop	FPIX0 p-spray	FPIX1 p-stop	FPIX1 p-spray
0°	0.25	0.00	0.02	N/A
5°	6.00	5.33	5.42	5.33
10°	10.99	10.24	10.49	10.27
15°	15.88	16.64	15.40	15.19
20°	21.06	21.57	20.40	N/A
30°	30.37	31.48	30.42	N/A

Precision of the alignment is about 0.1°

(*i.e.* Four runs of FPIX1 P-spray at 15°: *15.16, 15.22, 15.25, 15.16*)